A Complete Circuit Breaker Model for Calculating Very Fast Transient Voltages

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Abstract - Various studies have been carried out to determine the origin, the development and the effects of very fast transients (VFT) in GIS-Busbars. To date little knowledge exists on how VFT propagate through a high voltage circuit breaker, when the interrupter itself is the source of the VFT. For the development of circuit breakers it is important to know if these VFT are able to affect the dielectric coordination of the interrupter.

In order to determine transient voltages at different locations inside an interrupter unit a numerical model has been derived. The model approach represents the circuit breaker as a system of concatenated transmission lines. The simulations were compared to measurements of a real circuit breaker and proved the accuracy of the model in the frequency range from 9 kHz up to 500 MHz. This model allows future parameter studies which show the dependence of VFT overvoltages on the geometry of the circuit breaker.

Keywords – Very Fast Transients; VFT; VFTO, Model; Modelling Guidelines; Circuit Breaker

I. INTRODUCTION

Electrical apparatus designed for high voltage application are subject to a wide range of electrical stresses. Concerning the dielectric stress, there is the exposure to electric fields at power frequency as well as transient events e.g. lightning impulse, whereas the latter differ significantly from normal operation in terms of amplitude and frequency. A special kind of transient electrical event are very fast transient voltages (VFT). The exciting source of VFT is a breakdown between two contacts of different potential [1] and therefore a step-like change in voltage at these contacts which leads to travelling wave phenomena in the adjacent equipment. Under normal operating conditions these breakdowns occur only during disconnector or circuit breaker switching.

VFT are especially severe in SF6 insulated, metal enclosed systems [1]. There are two reasons for that: First, the metal enclosed, coaxial structure represents a good waveguide with low losses, and second, a breakdown in SF6 is very fast and is therefore able to provoke transients in the frequency range of several hundred MHz.

Disconnecter switching is well known to be the major source of VFT in gas insulated systems. Therefore, various modeling guidelines exist [2], [3], [4] on how to accurately simulate the development of VFT in gas insulated substations.

The effect of circuit breaker switching on the insulation properties of a substation is generally neglected since their high mechanical contact speed and their mode of application allow only few VFT to be excited. Due to this fact and the general focus of determining the dielectric coordination of whole substations, the detailed modeling of high voltage circuit breakers is not covered by the guidelines mentioned.

Since VFT are able to harm the dielectric coordination of gas insulated equipment it is important to investigate the propagation of VFT occurring in a circuit breaker. In order to identify certain overvoltages within the unit, an accurate model of a circuit breaker was developed and verified by measurements in the corresponding frequency domain.

II. MODELLING GUIDELINES

A. Selection of the Model

The model of the interrupter unit shall allow a simple but accurate parameter study in order to investigate the VFT development within the circuit breaker after an ignition. Moreover, the mechanism of impulse propagation in the circuit breaker and its dependency on the geometry shall be understood. Since both requirements are difficult to achieve using 3D FEM electrical field calculation, it was chosen to compute a model of a circuit breaker using network elements, i.e., transmission line models.

B. Investigated Specimen

In order to explicitly verify the accuracy of the model, the model calculation was based on a real circuit breaker unit. Doing so, the calculation of the model can be accompanied by measurements at the real unit. The circuit breaker used is a SF6 insulated, metal enclosed puffer breaker, rated Voltage 300 kV and maximum breaking current of 50 kA at f = 50 Hz. Fig. 1 shows a schematic, not scaleable cross section of the circuit breaker switching unit in half-open position.

Figure 1. Schematic drawing of switching unit under investigation
Since measurements at the terminals of the circuit breaker do not reveal information about the inner structure of the switching unit, the whole circuit breaker had to be disassembled. The model calculation and verification measurements started at the most inner part, the contact system. Afterwards the unit was stepwise extended until the whole circuit breaker could be measured and simulated.

C. Necessary Bandwidth

Using the $\lambda/10$ approximation [5] the lower frequency boundary for which travelling wave phenomena within a circuit breaker occur, was calculated to be $f_{\text{min}} = 10$ MHz in [6]. Based on an breakdown having less than 0.5 ns risetime (Fig. 1 in [6]) the upper frequency boundary results in $f_{\text{max}} = 1$ GHz [6].

Taking into account that the representation of the circuit breaker as a system of concatenated transmission lines will only give an accurate image of the transversal electromagnetic wave propagation in the circuit breaker (TEM Mode), the desired frequency band must be reduced. Due to the size of the specimen, higher electrical propagation modes can be excited as well. The first higher mode which can propagate in a coaxial system is the $H_{11}$-Mode [7] and its cutoff frequency $f_c$ is given by [7]:

$$f_c = \frac{c_0}{\lambda_c} = \frac{c_0}{2\sqrt{\varepsilon_r}(d + D)}$$

Using representative dimensions of the circuit breaker, e.g. diameter of outer conductor $D = 550$ mm and diameter of inner conductor $d = 239$ mm the cutoff-frequency results in $f_c = 241.9$ MHz.

Therefore the modeling system will not be able to represent the whole desirable frequency range $\Delta f = 10...1000$ MHz but according to the calculations in [6] it is expected that a frequency range $\Delta f = 10...500$ MHz will be sufficient to describe any transient event in a circuit breaker.

D. Circuit Breaker Model

The mathematical details for the model calculation can be found in [6] and are only briefly reviewed here. Due to the rotation symmetric design of the circuit breaker (Fig. 2a), each section of the unit having a constant inner and outer radius can be represented as a transmission line. Therefore the geometry of the circuit breaker can be fragmented into these sections (Fig. 2b) and described by the corresponding surge impedance $Z_w$ and the time delay $\Delta t$ for the travelling wave (Fig. 2c). In Fig. 2 the steps for model calculation and implementation are sketched exemplarily for the moving contact of the circuit breaker.

E. Connections to Circuit Breaker

With respect to the measurements at the circuit breaker, the electrical connections between the specific measured item and the measurement device must be added to the model since they strongly influence the measurement result. The most convenient way to implicate these connections into the model is by using a coaxial, tapered line.

Analogue to a straight coaxial line, where the surge impedance $Z_w$ is determined by the diameter of inner and outer conductors, the surge impedance of a tapered line is determined by the opening angle of inner and outer cone [8]:

$$Z_w = \frac{1}{2\pi\sqrt{\varepsilon_r}} \ln \left( \frac{\tan \frac{\nu_i}{2}}{\tan \frac{\nu_o}{2}} \right)$$

For the prevailing system opening angles of $\nu_i = 6.8^\circ$ and $\nu_o = 15.6^\circ$ were chosen, leading to a surge impedance of $Z_w = 50.09$ $\Omega$. The tapered lines which were actually build (Fig. 4a) have a surge impedance between 47.8 $\Omega$ and 49 $\Omega$ and a time delay $\Delta t = 3.952$ ns.

In order to minimize the excitation of higher modes, the connections between the 50 $\Omega$ tapered lines and the circuit breaker were modeled and built by smooth adaptation of the surge impedance to the connection of the specific measured item. The ‘conical connector’ in Fig. 7 and in Fig. 4b) is an example of such a connection. The connection according to Fig. 7 was included into the model by discretizing the cone into five elements, whereas the difference in surge impedance was kept constant between adjacent elements. Table I shows the values of the calculated elements with respect to the example shown in Fig. 7.

<table>
<thead>
<tr>
<th>No.</th>
<th>Impedance [\Omega]</th>
<th>Time delay [\mu s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>64.368</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>93.009</td>
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<td>0.12</td>
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<tr>
<td>4</td>
<td>150.29</td>
<td>0.073</td>
</tr>
<tr>
<td>5</td>
<td>178.93</td>
<td>0.045</td>
</tr>
</tbody>
</table>

TABLE I. ELEMENTS OF CONICAL CONNECTOR (FIG. 7)

Figure 2. Steps for the model calculation: a) analysis of the geometry, b) fragmentation into sections with constant radius and c) corresponding representation in the model.
III. MODEL IMPLEMENTATION AND SIMULATION

The model was implemented in Microcap 9, a P-Spice based simulation software.

To describe the properties of an electrical quadrupole \( A \) (Fig. 3) at a certain frequency it is common practice to determine the voltage at port 1, when port 2 is an open circuit and to determine the current at port 1 when port 2 is short circuited [9]. At higher frequencies it becomes difficult to define an open or short circuit, since these act more as capacitive or inductive element. Therefore the properties of an electrical network at higher frequencies are described by Scattering Parameters (\( S\)-Set) [5]. The \( S\)-Set describes the frequency dependant reflection coefficients of the network based on a 50 \( \Omega \) load. \( S_{11} \) and \( S_{22} \) represent the input reflection factors at port 1 and port 2 respectively. \( S_{12} \) and \( S_{21} \) represent the forward reflection factor from one port to the other. Since the measured item is a completely linear, time-invariant and passive component the \( S \)-Parameters will always be between 1…0 or 0…\( \infty \) dB. Furthermore \( S_{11} \) will be equal to \( S_{22} \) and \( S_{12} \) will be equal to \( S_{21} \). Therefore only the two parameters \( S_{11} \) and \( S_{12} \) are presented here.

![Figure 3. Measurement of scattering parameters](image)

IV. MEASUREMENT DEVICE

In order to determine the \( S\)-Set of certain items of the circuit breaker a vector network analyzer (VNA) with its appropriate calibration Kit was used. Connections were made using two 50 \( \Omega \) cables with N-Connectors. The tapered lines and any further connectors were produced at the Institute for Power Systems and High Voltage Technology, ETH Zurich, Switzerland. Fig. 4 shows the measurement device in use. Fig. 4a) VNA, Cables and the tapered line, Fig. 4b) the connecting cone (cf. Fig. 9).

![Figure 4. Measurement Setup – a) VNA, Cables and tapered line attached to a GIS-Pipe (outer conductor) – b) conical connector (inner conductor)](image)

V. VALIDATION OF MODELING PRINCIPLE

A. Small Scale Validation

In order to prove that the basic model and measurement principles lead to a correct result, a couple of calibrating measurements were performed. These investigations consisted of the comparison of the measurement of different cables having a well known surge impedance and time delay and their simulation. Fig. 5 shows an example of such a measurement. Fig. 5a) depicts the schematic drawing of the measurement setup and Fig. 5b) its representation in the model.

![Figure 5. Calibration measurement, schematic (a) and representation in the model (b)](image)

Fig. 6 shows the comparison between the measured and simulated parameters \( S_{11} \) and \( S_{12} \). The mean square error \( E \) (3) between the measured data \( m_i \) and the simulated data \( s_i \) in the frequency range from 9 kHz up to 900 MHz is 0.82 dB for \( S_{12} \) and 1.92 dB for \( S_{11} \).

\[
E = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (m_i - s_i)^2} \tag{3}
\]

The difference is mainly explained by the absence of any damping [6] in the model.

![Figure 6. Comparison between measurement and simulation of calibration setup verifies the basic model and simulation approach](image)

B. Large Scale Validation

Having shown that the basic modeling and measuring principles lead to a correct result in geometrically small setups,
it remains to be determined whether the model is accurate enough to describe setups with geometric dimensions in the size of a circuit breaker.

Fig. 7 represents a coaxial waveguide having an outer diameter of 550 mm and a diameter of the inner conductor of 239 mm (50 Ω) and 22 mm (192.5 Ω) respectively.

The comparison between measurement and simulation (Fig. 8) shows clearly the limitations of the system. The two curves show good agreement up to 500 MHz. Above this frequency the measured signal differs significantly from the simulated one. The increased damping, observable in the $S_{12}$-curve above 550 MHz indicates the excitation of higher wave propagation modes. Between 9 kHz and 500 MHz the mean square error (3) is 0.43 dB for $S_{12}$ and 1.32 dB for $S_{11}$.

**VI. RESULTS**

After the basic validation of the system, the analysis of the circuit breaker components was performed. Beside the immobile and the moving contact side, also the full circuit breaker in open, slightly open and closed position was characterized. Due to the limitations in bandwidth observed during the calibrating measurement the mean square errors (3) between measurement and simulation are further on always calculated in the frequency range from 9 kHz to 500 MHz.

A. **Immobile Contact System**

The measurement setup and model of the immobile contact of the circuit breaker are shown in Fig. 9. The according measurement and simulation data are shown in Fig. 10. The comparison proves that the model calculated is an accurate representation of the circuit breaker contact. The mean square error (3) between measured and simulated data is in the order of 2.79 dB for $S_{12}$ and 2 dB for $S_{11}$.

B. **Moving Contact System**

The schematic drawing and representation in the model of the moving contact system of the circuit breaker can be found in Fig. 2. Simulated and measured data are compared in Fig. 11. The mean square error (3) of the two curves are 0.81 dB and 3.02 dB for $S_{12}$ and $S_{11}$ respectively and prove a good agreement between simulation and measurement.
VII. Discussion

Applying the herein introduced modeling guidelines lead to a model of a high voltage circuit breaker which incorporates all the internal irregularities in design and is valid in a very high frequency range, i.e. up to 500 MHz.

It has to be pointed out that measurements in the range of hundreds of MHz applied at a passive system with a geometrical size far bigger than the shortest electrical wavelength is very ambitious. Therefore the measurements and the calculation of the model have to be performed with maximum care in order to get an accurate result.

Using this model a detailed parameter study becomes possible which would reveal the dependencies of certain overvoltages within the interrupter unit on its geometry. At the point where a configuration for maximum overvoltage occurrence is found, it would be meaningful to investigate whether these overvoltages lead to a failure of the dielectric coordination of the circuit breaker.

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